

Carbon, Nitrogen and Oxygen Abundances in Atmospheres of the 5-11 M_{\odot} B-type Main Sequence Stars

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ABSTRACT

Fundamental parameters and the carbon, nitrogen and oxygen abundances are determined for 22 B-type stars with distances $d \leq 600$ pc and slow rotation ($v \sin i \leq 66$ km s⁻¹). The stars are selected according to their effective temperatures T_{eff} and surface gravities $\log g$, namely: T_{eff} is between 15300 and 24100 K and $\log g$ is mostly greater than 3.75; therefore, stars with medium masses of 5-11 M_{\odot} are selected. Theory predicts for the stars with such parameters that the C, N and O abundances in their atmospheres should correspond to their initial values. Non-LTE analysis of C II, N II and O II lines is implemented. The following mean C, N and O abundances are obtained: $\log \epsilon(\text{C}) = 8.31 \pm 0.13$, $\log \epsilon(\text{N}) = 7.80 \pm 0.12$ and $\log \epsilon(\text{O}) = 8.73 \pm 0.13$. These values are in very good agreement with recent data on the C, N and O abundances for nearby B stars from other authors; it is important that different techniques are applied by us and other authors. When excluding for the stars HR 1810 and HR 2938, which can be mixed, we obtain the following mean abundances for the remaining 20 stars: $\log \epsilon(\text{C}) = 8.33 \pm 0.11$, $\log \epsilon(\text{N}) = 7.78 \pm 0.09$ and $\log \epsilon(\text{O}) = 8.72 \pm 0.12$; these values are in excellent agreement with a present-day Cosmic Abundance Standard (CAS) of Nieva & Przybilla.

The derived mean N and O abundances in unevolved B stars are very close to the solar photospheric abundances, as well as to the protosolar ones. However, the mean C abundance is somewhat lower than the solar one; this small but stable carbon deficiency is confirmed by other authors. One may suggest two possibilities to explain the observed C deficiency. First, current non-LTE computations of C II lines are still partially inadequate. In this case the C deficiency is invalid, so one may conclude that the Sun and the local unevolved B stars have the same metallicity. This would mean that during the Sun's life (i.e., for the past $4.5 \cdot 10^9$ yr) the metallicity of the solar neighbourhood has not markedly changed; so, an intensive enrichment of the solar neighbourhood by metals occurred before the Sun's birth. Second, the C deficiency in the local B stars is valid; it is supposed that the Sun can migrate during its life from inner parts of the Galactic disk where it has born, so its observed chemical composition can differ from the composition of young stars in its present neighbourhood.

Key words: stars: abundances - stars: evolution - stars: early-type

1 INTRODUCTION

Some recent works show that the metallicity of young stars in the solar neighborhood is very close to the Sun's metallic-

ity. In particular, it was shown by Lyubimkov et al. (2010) that the mean iron abundance in the atmosphere of 48 A-, F- and G-type supergiants with distances $d < 700$ pc is $\log \epsilon(\text{Fe}) = 7.48 \pm 0.09$, a value that coincides with the solar abundance $\log \epsilon_{\odot}(\text{Fe}) = 7.50 \pm 0.04$ (Asplund et al. 2009). Earlier it was found for local early B-type stars, the progenitors of AFG supergiants, that their mean magnesium abun-

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dance is $\log \epsilon(\text{Mg}) = 7.59 \pm 0.15$ (Lyubimkov et al. 2005), that is equal to the solar abundance $\log \epsilon_{\odot}(\text{Mg}) = 7.60 \pm 0.04$ (Asplund et al. 2009). One may mention also the Fe abundance obtained by Luck, Kovtyukh & Andrievsky (2006) for Cepheids in the solar vicinity, as well as the Fe and Mg abundances found by Fuhrmann (2004) for nearby F, G and K dwarfs and subgiants of the thin Galactic disk. Moreover, it was found for B-type stars in the Orion OB1 association that their S and O abundances are very close to the solar ones; see Daflon et al. (2009) and Simón-Díaz (2010), respectively. Nieva & Simón-Díaz (2011) showed that the B stars in the Orion OB1 association show good agreement with the Sun in their C, N, O, Mg, Si, and Fe abundances.

Just three years ago, the problem of metallicity of young stars seemed far from simple. It was shown by several authors that the metal abundances in nearby B-type stars were somewhat less than in the Sun (see, e.g., Morel's 2009 review). In particular, the derived C, N and O abundances of B-type stars tended to be less than in the Sun. Two possible explanations were considered, namely: (i) there is a real slight deficiency of C, N and O in the stellar atmospheres, e.g., connected with stellar evolution or (ii) the C, N and O abundances were systematically underestimated in some studies. Then in 2003–2008, studies were reported where the N and O abundances in B stars were close to the revised N and O solar abundances based on a three-dimensional model of the Sun's atmosphere; the C abundance continued to show a small deficiency (see, e.g., Herrero 2003; Herrero & Lennon 2004 and Przybilla 2008). In order to investigate the possible metallicity difference between the Sun and young stars, we undertook an accurate analysis of the C, N and O abundances for a rather large sample of nearby early and medium B-type stars in the main sequence (MS) evolutionary phase. (Note that up-to-date results for C, N and O appeared during our analyses will be discussed in Section 7).

The C, N and O abundances in early and medium B-type stars are determined here from C II, N II and O II spectral lines. These lines are rather sensitive to two fundamental parameters of the stars, namely their effective temperatures T_{eff} and surface gravities $\log g$. Recently, we showed (Lyubimkov et al. 2009, 2010) that a significant improvement in the accuracy of the $\log g$ values can be obtained through application of van Leeuwen's (2007) new reduction of the Hipparcos parallaxes. Using these new parallaxes in an analysis of A, F and G supergiants, we obtained $\log g$ with very high accuracy for stars with distances $d < 700$ pc. Now, we apply this method in the present study of B-type MS stars.

As far as the effective temperature T_{eff} is concerned, there is some difference in various T_{eff} scales for B stars that is especially significant for the hottest B stars with $T_{\text{eff}} \geq 25000$ K. Therefore, we consider relatively cool B stars with $T_{\text{eff}} \leq 24000$ K, for which the T_{eff} estimates are more reliable. Moreover, we consider mostly those B stars with $\log g \geq 3.75$, i.e., stars rather far from the termination of the MS phase, in order to exclude possible evolutionary changes in the C, N and O abundances. In other words, we try to determine the *initial* abundances of these elements in such young stars.

Carbon, nitrogen and oxygen participate in the CNO-cycle, which is the main source of energy of the B-type MS stars. The C and N abundances change significantly in stellar interiors during the MS phase (the O abundance shows

smaller alterations). It has been predicted that the C, N and O abundances can change markedly in surface layers too, if rotationally-induced mixing in the MS phase occurs (Heger & Langer, 2000; Frischknecht et al. 2010). The changes in the surface C, N and O abundances by the MS phase termination depend strongly on the mass M and the initial rotational velocity v_0 of a star: the greater M and v_0 the stronger the predicted final alterations. Since our goal is to obtain the initial abundances, we consider the B-type stars with medium masses (5–11 M_{\odot}) that are not close to the MS phase termination. Their observed rotational velocities are rather small, too ($v \sin i \leq 66$ km s $^{-1}$) which implies that the majority of the selected stars are slow rotators but an admixture of rapid rotators observed at high angles of inclination may be present.

2 SELECTION OF STARS

We have studied previously a large sample of early and medium B-type stars in the MS phase; results have been published in four papers (Lyubimkov et al. 2000, 2002, 2004 and 2005; hereinafter Papers I, II, III and IV, respectively). In particular, in Paper III we determined from He I lines the helium abundance He/H and the projected rotational velocity $v \sin i$ for 102 B stars. The $v \sin i$ values were found to range from 5 to 280 km s $^{-1}$; such a large variation allowed us to analyze a relation between the helium abundances and rotational velocities. The used He I lines are strong in spectra of early and medium B stars, so their equivalent widths can be measured without problems even for the stars with rather high $v \sin i$. On the contrary, the C II, N II and O II lines used in the C, N and O abundance analysis are significantly weaker, so measurements of their equivalent widths for $v \sin i > 100$ km s $^{-1}$ are difficult, especially for stars with effective temperatures $T_{\text{eff}} < 17000$ K. As a result, we found that only 54 stars with $v \sin i < 100$ km s $^{-1}$ from our original list are suitable for the C, N and O abundance analysis.

There are other limitations as well. One concerns the effective temperatures T_{eff} of B stars. It is known that the T_{eff} scales of various authors for B stars are different, and the difference increases with T_{eff} , so the differences are especially large for the hottest B stars with $T_{\text{eff}} \geq 25000$ K (see, e.g., a comparison of some T_{eff} scales in Daflon, Cunha & Butler 2004). We determined in Paper II the T_{eff} and $\log g$ values for more than 100 B stars and confirmed that uncertainties in the T_{eff} are especially great for $T_{\text{eff}} \geq 25000$ K. Therefore, we selected from our original list only stars with $T_{\text{eff}} \leq 24000$ K. The next limitation regards another fundamental parameter, the surface gravity $\log g$. In order to exclude as far as possible evolutionary effects on the observed C, N and O abundances, we consider stars which are not close to the MS phase termination. Therefore, the selected stars have mostly $\log g > 3.75$.

One more limitation regards the stellar parallaxes π , which are used by us as the principal indicator of the surface gravity $\log g$. Using van Leeuwen's (2007) catalog, we selected stars with $\pi \geq 1.67$ mas, i.e., with distances $d \leq 600$ pc (mas = milliarcsecond). Selection of stars with smaller π values would reduce markedly the accuracy of the derived surface gravities $\log g$.

The final list of B stars selected is presented in Table 1;

Table 1. Basic parameters of programme B stars

HR	HD	π , mas	d , pc	$v \sin i$, km s ⁻¹	T_{eff} K	$\log g$ cgs	M/M_{\odot}
38	829	1.81±0.42	552 ±98	11.5±1.5	19220±510	3.83±0.15	7.6
1617	32249	4.42±0.23	226 ±11	45.0±1.0	18570±20	3.87±0.04	7.1
1640	32612	1.76±0.41	568±102	53.5±1.5	19750±230	3.81±0.15	8.0
1781	35299	3.72±0.32	269 ±21	5.0 ±2.5	23700±410	4.27±0.07	8.9
1810	35708	5.20±0.21	192 ± 7	24.0±2.0	21040±520	4.11±0.07	7.7
1820	35912	2.53±0.55	395 ±67	13.5±2.0	19370±380	4.05±0.19	7.0
1923	37356	2.03±0.47	493 ±88	17.5±3.0	21400±630	3.78±0.16	9.5
1933	37481	2.44±0.39	410 ±55	66.0±2.5	24090±850	4.14±0.13	9.7
2058	39777	2.80±0.53	357 ±55	21.5±2.0	21720±370	4.24±0.16	7.7
2205	42690	2.73±0.28	366 ±34	9.8 ±3.5	19390±310	3.74±0.04	8.1
2344	45546	3.00±0.24	333 ±25	61.0±2.5	19420±570	3.76±0.07	8.0
2756	56342	5.19±0.22	193 ± 8	26.0±1.5	16590±390	4.06±0.04	5.4
2824	58325	1.67±0.36	599±101	12.5±2.5	20210±450	3.86±0.16	8.4
2928	61068	1.93±0.28	518 ±64	26.0±1.5	23650±850	3.83±0.11	11.2
3023	63271	1.99±0.33	503 ±69	42.0±1.5	22400±200	3.86±0.12	9.7
7426	184171	3.80±0.16	263 ±11	29.5±2.0	16540±850	3.60±0.07	6.8
7862	196035	3.56±0.46	281 ±32	34.0±1.5	17750±550	4.19±0.09	5.7
7996	198820	1.87±0.33	535 ±78	35.0±1.5	15980±400	3.60±0.12	6.5
8385	209008	3.07±0.42	326 ±38	19.0±3.0	15360±240	3.76±0.10	5.6
8549	212883	2.17±0.63	461 ±95	8.0 ±3.0	20400±680	3.97±0.21	7.8
8768	217811	3.07±0.58	326 ±50	8.0 ±4.0	18090±730	3.94±0.16	6.5
9005	223128	2.19±0.27	457 ±49	15.5±2.5	22340±870	3.79±0.11	10.5

it contains 22 objects in all. We present there for each star its HR and HD numbers, parallax π with its error from van Leeuwen's (2007) catalog and corresponding distance $d = 1/\pi$, where π is in arcseconds. The presented errors in distances d are evaluated with the formula given by van Leeuwen's (2007, p.86). The projected rotational velocities $v \sin i$ with their uncertainties from Paper III are provided, too; note that the $v \sin i$ values have been found in Paper III from profiles of six He I lines. Other parameters in Table 1, namely the effective temperature T_{eff} , surface gravity $\log g$ and mass M , will be determined below.

The masses M of the selected stars are between 5 and 11 M_{\odot} , and their projected rotational velocities are $v \sin i \leq 66 \text{ km s}^{-1}$. Therefore, we may hope that possible evolutionary changes to the surface N and O abundances due to the rotationally-induced mixing in the MS phase are minimized. However, we need to be confident that the derived N and O abundances of these stars are really close to their *initial* abundances; in other words, they have not been altered by mixing. In this connection, the stars with the lowest surface gravities $\log g$ are of special interest, because they are closer to the MS phase termination than other programme stars and, therefore, may show somewhat altered C, N and O abundances. There are seven stars in Table 1 with $\log g < 3.80$, specifically with $\log g = 3.60$ -3.79. Their masses are $M = 5.6$ -10.5 M_{\odot} ; the projected rotational velocities are $v \sin i = 9$ -35 km s^{-1} for six stars and $v \sin i = 61 \text{ km s}^{-1}$ for HR 2344. It follows from Frischknecht et al.'s (2010) computations that for the model with $M = 12 M_{\odot}$ and initial rotational velocity $v_0 = 62 \text{ km s}^{-1}$ the surface value $\log \epsilon(\text{C})$ decreases only by 0.02 dex and $\log \epsilon(\text{N})$ increases only by 0.05 dex by the MS end. Therefore, for the lower masses and rotational velocities, like that for 7 stars in question, the expected changes in $\log \epsilon(\text{C})$ and $\log \epsilon(\text{N})$ are still smaller, whereas the changes in $\log \epsilon(\text{O})$ are imperceptible (according to the theory, oxygen shows smaller changes than carbon and nitrogen. So, the derived $\log \epsilon(\text{C})$, $\log \epsilon(\text{N})$

and $\log \epsilon(\text{O})$ values for all programme stars are anticipated to be very close to the initial abundances.

3 OBSERVATIONS AND EQUIVALENT WIDTHS

We used here the same high-resolution spectra as in Papers I-IV. The spectra were acquired in 1996-1998 at two observatories, namely the McDonald Observatory (McDO) of the University of Texas and the Crimean Astrophysical Observatory (CrAO). At the McDO the 2.7-m telescope and the Tull coude echelle spectrometer was employed (Tull et al. 1995). The resolving power was $R = 60000$ and the typical signal-to-noise ratio was between 100 and 300. At the CrAO we observed on the 2.6-m telescope with the coude spectrograph. In this case we had $R = 30000$ and a signal-to-noise ratio between 50 and 200. A more detailed description of the observations and reductions of spectra was presented in Paper I. It should be noted that spectral intervals of about 70 Å centered on He I lines were recorded at the CrAO. Since these intervals contain few C II, N II and O II lines, we used mostly the McDO echelle spectra for selection of the lines and measurements of their equivalent widths.

When measuring the equivalent widths W , we found that rarely could the C II, N II and O II lines be accurately fitted by Gaussian profiles. Therefore, in most cases the W values were measured by direct integration. We checked for possible blending of the lines using the database VALD (Kupka et al. 1999, Heiter et al. 2008) and predicted W values for models based on parameters T_{eff} and $\log g$ from Paper II. Only those lines were selected where the estimated blending was markedly less than 10 per cent. It should be noted that the number of measured lines is different for different stars; this number depends on the effective temperature T_{eff} and the observed rotational velocity $v \sin i$. The lines in question are especially weak for stars with $T_{\text{eff}} < 17000 \text{ K}$,

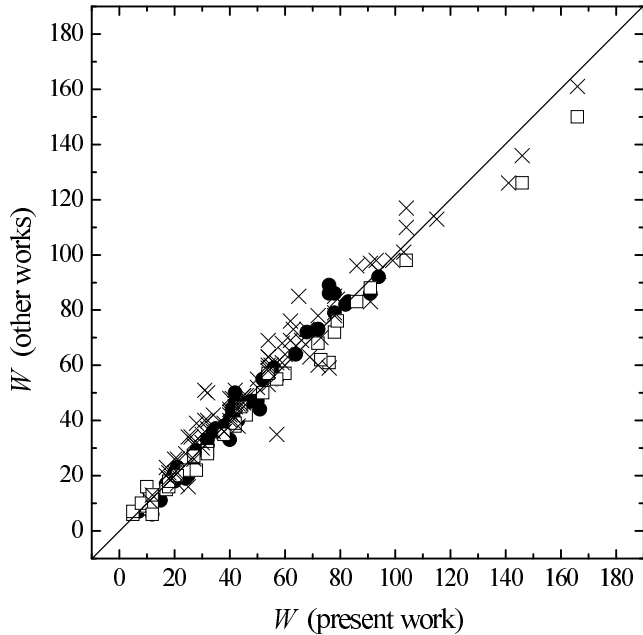


Figure 1. Comparison of our equivalent widths (in mÅ) of N II and O II lines with data from other works, namely: Gies & Lambert (1992) - squares, Cunha & Lambert (1992, 1994) - filled circles, and Kilian & Nissen (1989) - crosses. Straight line corresponds to the equal W values.

so in this case the W values are measurable only for stars with low $v \sin i$. For some stars it was possible to obtain W only for a few lines including the relatively strong lines C II 4267 Å and N II 3995 Å. We found that use of these lines in the C and N abundance determination is questionable, so they were excluded from the analysis (see below).

It is interesting to compare the measured equivalent widths W with other measurements. In Fig. 1 we compare our W values with the data from three sources, namely Gies & Lambert (1992), Cunha & Lambert (1992, 1994) and Kilian & Nissen (1989), where there are 3, 4 and 4 stars in common, respectively. One may see that there is good agreement for lines with $W < 120$ mÅ, and only the few lines with $W > 120$ mÅ show a small systematic discrepancy. So, one may conclude that there is, in general, good agreement between our and previous W measurements.

4 NON-LTE COMPUTATIONS

4.1 Necessity for a non-LTE approach

Departures from local thermodynamic equilibrium (LTE) have an influence on computations of C II, N II and O II lines for early B stars. Using both LTE and non-LTE approach, Gies & Lambert (1992) found that differences in the N and O abundances between these two cases are rather small on average, but for some stars they exceed 0.2 dex. An appreciable difference due to the non-LTE effects can appear for the derived microturbulent parameter V_t . According to Korotin et al. (1999b), non-LTE corrections to the oxygen abundance in early B stars can attain 0.2-0.3 dex.

In order to study the non-LTE effect on C II, N II and

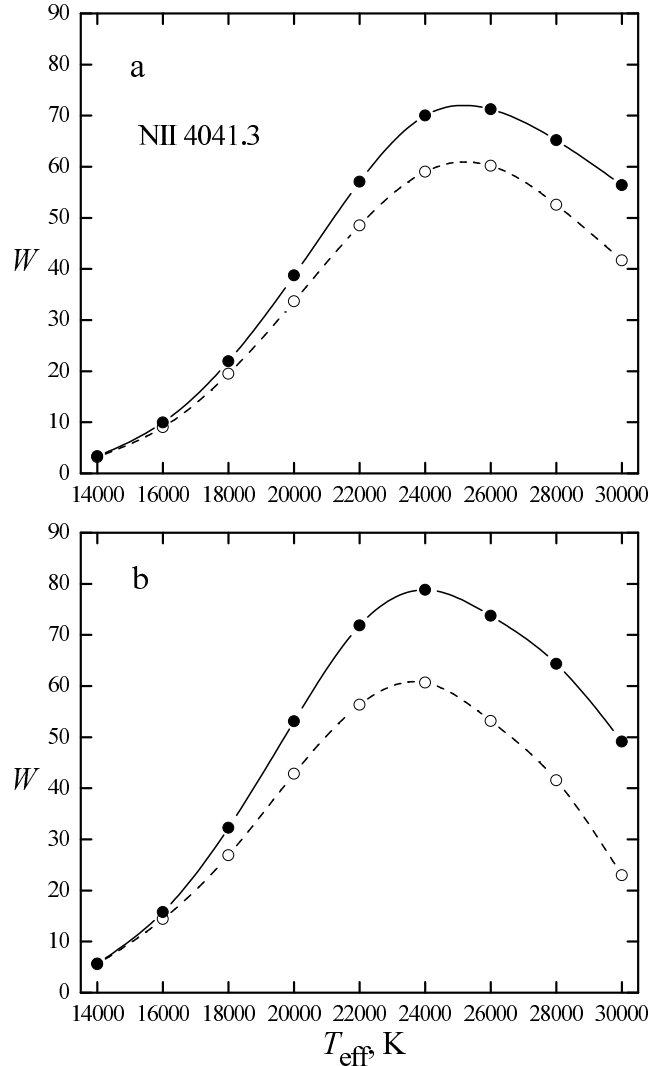


Figure 2. Comparison of computed equivalent widths of the N II 4041.3 Å line for non-LTE (solid curve) and LTE (dashed curve). Computations are implemented for (a) $\log g = 4.0$ and (b) $\log g = 3.5$.

O II lines in more detail, we performed both LTE and non-LTE calculations for all the lines used in our analysis - see the next section for details. We show as an example in Fig. 2 and Fig. 3 results of the calculations for two lines, namely N II 4041.3 Å and O II 4414.9 Å (the solar N and O abundances are adopted). Equivalent widths W of the lines are displayed as a function of the effective temperature T_{eff} for (a) $\log g = 4.0$ and (b) $\log g = 3.5$. For these lines, as well as for other used lines, the W values in the non-LTE case are greater than in the LTE one. The difference is small for stars with $T_{\text{eff}} < 18000$ K but increases for hotter stars. Fig. 2 shows that in the W maximum region of the line N II 4041.3 Å, i.e. at $T_{\text{eff}} = 25000$ K (a) or 24000 K (b), the difference is 18 per cent for $\log g = 4.0$ and 30 per cent for $\log g = 3.5$. According to Fig. 3, the discrepancy between non-LTE and LTE for the O II 4414.9 Å line is more significant. In particular, in the W maximum region at $T_{\text{eff}} = 28000$ K (a) or 26000 K (b) the difference is about 40 per cent for $\log g = 4.0$ and 55 per cent for $\log g = 3.5$. So,

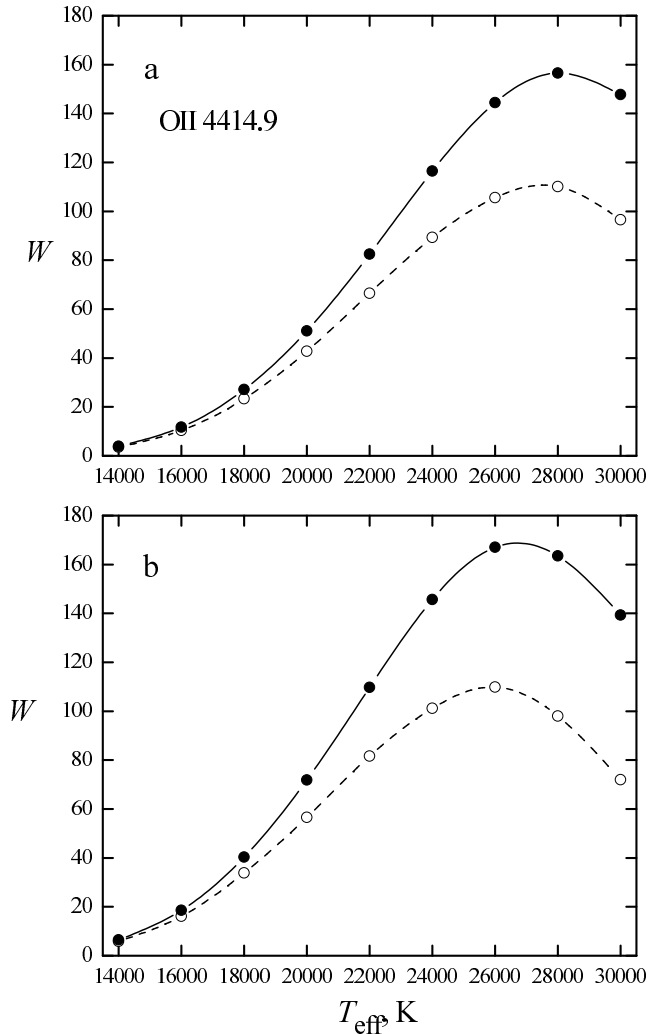


Figure 3. Comparison of computed equivalent widths of the O II 4414.9 Å line for non-LTE (solid curve) and LTE (dashed curve). Computations are implemented for (a) $\log g = 4.0$ and (b) $\log g = 3.5$.

it follows from our computations that departures from LTE for B stars with $T_{\text{eff}} > 20000$ K are substantial. Therefore, we use a non-LTE approach for all lines and all stars in the present work.

Our analysis showed that the non-LTE influence on derived abundances leads to a significant decrease of the microturbulent parameter V_t , especially for relatively hot B stars with $T_{\text{eff}} > 20000$ K. The non-LTE V_t values for such stars can decrease by a factor of about two as compared with the LTE ones. Therefore, we confirmed Gies & Lambert's (1992) conclusion about the strong dependence of the V_t derivation on the LTE or non-LTE approach.

4.2 Non-LTE computations and selection of lines

For the non-LTE computations of C II, N II and O II lines, we applied the code MULTI created by Carlsson (1986) and updated by S.A.Korotin (see Korotin et al. 1998, 1999 a,b). This code, as well as all input data including the N and O model atoms was kindly provided to us by S.A. Korotin

(the carbon model atom is taken from Sigut, 1996). Note that we used this same code in a non-LTE analysis of the nitrogen abundance from N I lines for A- and F-type supergiants (Lyubimkov et al. 2011). Atomic data for C II, N II and O II lines are taken from the database VALD (Kupka et al. 1999; Heiter et al. 2008). The list of the lines used is presented in Table 2 including their lower excitation potentials E_l and the oscillator strengths $\log gf$. In the computations we used, as in Paper III and IV, the plane-parallel blanketed LTE model atmospheres, which were computed by us with the code ATLAS9 (Kurucz 1993) for the corresponding parameters T_{eff} and $\log g$ of programme stars. Our approach is what has been termed a hybrid method, i.e., LTE model atmospheres are combined with non-LTE line formation.

As mentioned above, 22 B stars with effective temperatures $T_{\text{eff}} \leq 24000$ K were selected for the present work. However, we plan to analyze later the C, N and O abundances for hotter B stars from our original list with T_{eff} up to 30000 K. Therefore, from the outset, we performed non-LTE computations of C II, N II and O II lines for B stars with effective temperatures T_{eff} up to 30000 K and rotational velocities $v \sin i < 100 \text{ km s}^{-1}$. As a result, we considered 54 objects in all instead of 22. Their parameters T_{eff} and $\log g$ were taken from Paper II as a first approximation.

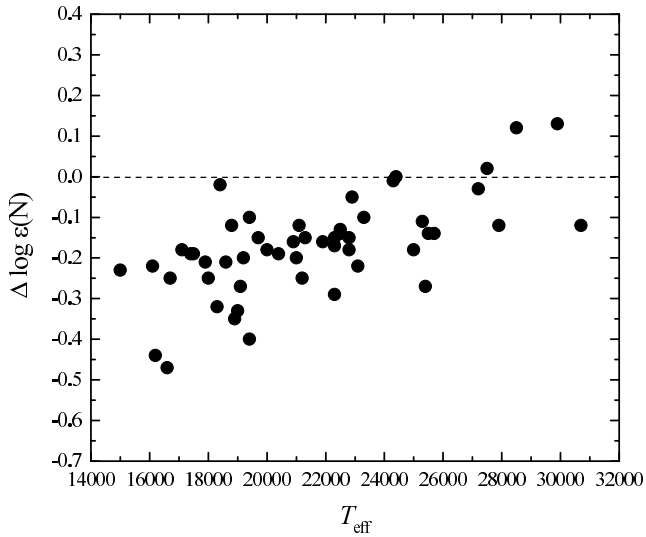
We compared for each of the 54 stars the non-LTE C, N and O abundances derived from individual C II, N II and O II lines with the mean C, N and O abundances obtained from other lines. We found that some lines display a systematic discrepancy. In particular, the strongest C II line in the visible spectral region, namely the line C II 4267 Å, showed a systematic difference in $\log \epsilon(\text{C})$ for hotter stars of our sample: for stars with T_{eff} between 20000 and 24000 K the $\log \epsilon(\text{C})$ underestimation from 4267 Å is about 0.2-0.7 dex. A tendency of 4267 Å to lower the $\log \epsilon(\text{C})$ values for early B stars has been noted earlier. Meantime, a few attempts have been made to update the non-LTE calculations of this line by using a more detailed model atom. In particular, Sigut's (1996) computations improved markedly the agreement with observed equivalent widths of the line. We applied Sigut's model atom in our non-LTE calculations of C II lines. Nevertheless, it was impossible to eliminate the significant discrepancy between 4267 Å and other C II lines.

Furthermore, a systematic difference was found for the strongest N II line in the visible spectral region: this line at N II 3995 Å is frequently used in analyses of B and O stars. In Fig. 4 the difference between the $\log \epsilon(\text{N})$ values determined from the N II 3995 Å line and the mean N abundances (without 3995 Å) is shown as a function of T_{eff} . The underestimate is obviously correlated with T_{eff} with the largest underestimation (up to 0.2-0.4 dex) occurring for the coolest B stars of the sample. If included in the collection of N II lines, this line has a significant influence on the determination of the microturbulent parameter V_t . It is clear that the 3995 Å line should be excluded from the analysis of our programme stars with $T_{\text{eff}} \leq 24000$ K. Nevertheless, as Fig. 4 shows, for the stars with $T_{\text{eff}} > 26000$ K this line displays no systematic discrepancy; therefore, for such hot stars use of 3995 Å in the N abundance analysis is likely to be permissible.

Thus, we excluded from further analyses the C II 4267 Å and N II 3995 Å lines. Moreover, two O II lines, namely 4093 Å and 4705 Å, were excluded because they show also

Table 2. List of the used C II, N II and O II lines

CII λ , Å	E_l , eV	$\log gf$	NII λ , Å	E_l , eV	$\log gf$	OII λ , Å	E_l , eV	$\log gf$
3918.969	16.332	-0.533	4035.080	23.125	0.623	4072.150	25.650	0.552
3920.681	16.333	-0.232	4041.310	23.142	0.853	4075.859	25.665	0.692
5137.253	20.702	-0.940	4043.533	23.132	0.743	4085.114	25.650	-0.188
5139.175	20.704	-0.740	4199.977	23.246	0.030	4132.800	25.832	-0.066
5143.495	20.704	-0.212	4227.738	21.600	-0.068	4156.533	25.849	-0.696
5145.165	20.710	0.189	4447.028	20.409	0.285	4185.451	28.358	0.604
5151.083	20.710	-0.179	4601.478	18.466	-0.428	4303.821	28.822	0.640
5648.070	20.704	-0.424	4607.154	18.462	-0.507	4317.134	22.966	-0.385
5662.456	20.710	-0.249	4613.870	18.466	-0.665	4395.939	26.249	-0.169
6578.048	14.449	-0.026	4621.394	18.466	-0.514	4414.889	23.442	0.171
6582.873	14.449	-0.328	4630.535	18.483	0.094	4452.342	23.442	-0.789
6779.940	20.704	0.024	4643.083	18.483	-0.359	4590.978	25.661	0.350
6783.904	20.710	0.304	4678.136	23.572	0.434	4610.197	29.063	-0.170
			4987.377	20.940	-0.555	4638.854	22.966	-0.332
			5002.700	18.462	-1.021	4641.813	22.980	0.054
			5005.147	20.666	0.592	4649.139	22.999	0.308
			5007.330	20.940	0.171	4650.839	22.966	-0.361
			5010.619	18.466	-0.606	4661.632	22.980	-0.277
			5025.654	20.666	-0.546	4673.735	22.980	-1.088
			5045.092	18.483	-0.407	4676.237	22.999	-0.395
			5666.628	18.466	-0.045	4701.180	28.830	0.088
			5679.554	18.483	0.250	4703.163	28.513	0.262
			5686.213	18.466	-0.549	4890.865	26.305	-0.436
			6482.043	18.497	-0.162	4906.841	26.305	-0.160
						4941.064	26.554	-0.054
						4943.000	26.561	0.239

**Figure 4.** Difference between the N abundance derived from the N II 3995 Å line and the mean N abundance obtained from all other N II lines.

a systematic trend with T_{eff} . It is interesting that in the recent work of Nieva & Przybilla (2012), where updated model atoms for carbon and nitrogen were applied, the lines C II 4267 Å and N II 3995 Å did not show a marked difference from other lines. Therefore, the above-mentioned discrepancies for the lines C II 4267 Å and N II 3995 Å and two O II lines are likely to be due to some incompleteness of the C, N and O model atoms used in our analysis (Korotin et al. 1998, 1999 a,b).

5 EFFECTIVE TEMPERATURES T_{eff} AND SURFACE GRAVITIES $\log g$

Effective temperatures T_{eff} and surface gravities $\log g$ of more than 100 B stars have been determined by us in Paper II. Now, we redetermine these parameters for the selected 22 stars using the new stellar parallaxes of van Leeuwen (2007) as principal indicators of $\log g$. Other indicators of $\log g$ used in Paper II, namely the β -index and equivalent widths of the Balmer lines H_β and H_γ , are considered now only for comparison. As far as the effective temperature T_{eff} is concerned, we use the same two indicators as in Paper II, i.e., the colour indices Q and $[c_1]$ in the photometric systems *UBV* and *uvby*, respectively (as known, both indices are insensitive to interstellar extinction).

Observed Q values were determined with photometric data from Mermilliod & Mermilliod's (1994) and Mermilliod's (1994) catalogues. Observed $[c_1]$ and β indices are found from Hauck & Mermilliod's (1998) catalogue. Observed equivalent widths $W(H_\beta)$ and $W(H_\gamma)$ are provided in Paper I. These observed parameters are compared with the computed values. Computations of $W(H_\beta)$ and $W(H_\gamma)$ for a large number of model atmospheres have been presented by Kurucz (1993). Colour indices for calculations of Q and $[c_1]$ are taken by us from Castelli & Kurucz (2003). Computed β values are published by Castelli & Kurucz (2006).

As a typical example of the combined T_{eff} and $\log g$ determination, we show in Fig. 5 the diagram for the star HR 1810. This is the standard $T_{\text{eff}} - \log g$ diagram, where various curves are the loci from the theoretical models which predict the observed value for each of the considered parameters (Q , $[c_1]$, etc.). The locus that is set by parallax π is virtually a straight line; it depends on T_{eff} very slightly.

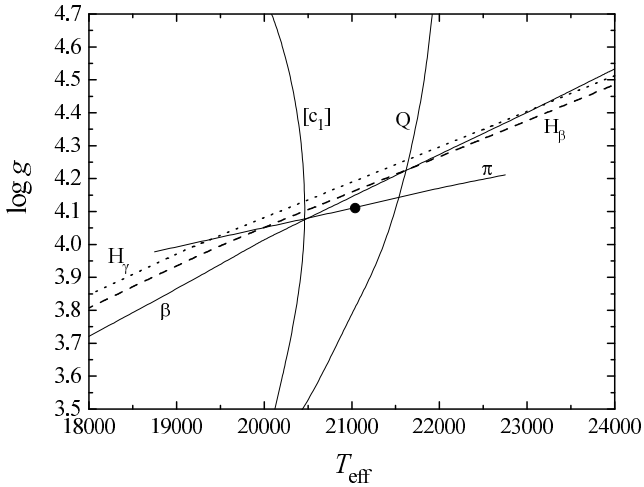


Figure 5. The T_{eff} - $\log g$ diagram for the star HR 1810. The filled circle corresponds to the adopted parameters $T_{\text{eff}} = 21040$ K and $\log g = 4.11$.

Note that application of π was described in detail by us earlier (Lyubimkov et al. 2009, 2010). In the case of HR 1810 the parallax is rather large and known with a good accuracy, namely $\pi = 5.20 \pm 0.21$ mas. When the effective temperature T_{eff} is fixed, the surface gravity of the star is derived reliably from π ; in fact, the uncertainty in $\log g$ is only ± 0.03 .

Two indicators of T_{eff} , namely indices Q and $[c_1]$, show in Fig. 5 somewhat different temperatures T_{eff} ; the difference is about 1000 K. We adopted the mean T_{eff} value, so the final parameters of the star HR 1810 are $T_{\text{eff}} = 21040 \pm 520$ K and $\log g = 4.11 \pm 0.07$ (filled circle in Fig. 5). Fig. 5 shows that there is good agreement between the value $\log g = 4.11$ derived from the parallax and the $\log g$ estimates from the Balmer lines and β -index. Using this technique, we obtained the parameters T_{eff} and $\log g$ for all programme stars; these values and their uncertainties are presented in Table 1.

Fig. 5 displays one feature in the T_{eff} determination for early B stars, which has been already noted by us in Paper II, namely: there is a systematic discrepancy between indices Q and $[c_1]$ as indicators of the T_{eff} . An especially hotter T_{eff} from Q as compared with $[c_1]$ is found for B stars with $T_{\text{eff}} > 24000$ K, i.e., for spectral subtypes B0-B1.5. Our consideration of this discrepancy for B0-B1.5 stars in Paper II led to the conclusion that the $T_{\text{eff}}([c_1])$ values are more correct than $T_{\text{eff}}(Q)$. Theoretical Q values based on Kurucz's (1993) computed indices $(U - B)$ and $(B - V)$ have been corrected in order to eliminate disagreement between $T_{\text{eff}}(Q)$ and $T_{\text{eff}}([c_1])$. Therefore, the index $[c_1]$ has been adopted as a principal indicator of T_{eff} . Now that we use the computed $(U - B)$ and $(B - V)$ indices from Castelli & Kurucz (2003), we find that the discrepancy between $T_{\text{eff}}(Q)$ and $T_{\text{eff}}([c_1])$ decreases but does not disappear.

One may see from Table 1 that our programme B stars have effective temperatures from 15360 to 24090 K. For these relatively cool B stars the difference between $T_{\text{eff}}(Q)$ and $T_{\text{eff}}([c_1])$ leads to an uncertainty in T_{eff} of between ± 20 and ± 870 K with a mean value of ± 500 K. When comparing such accuracy with data on T_{eff} from other authors, one may conclude that the accuracy is plenty good enough.

It is interesting to compare the T_{eff} and $\log g$ values

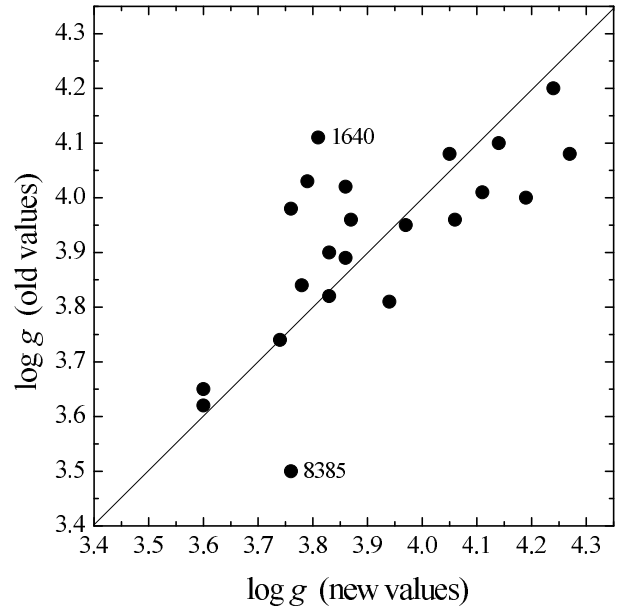
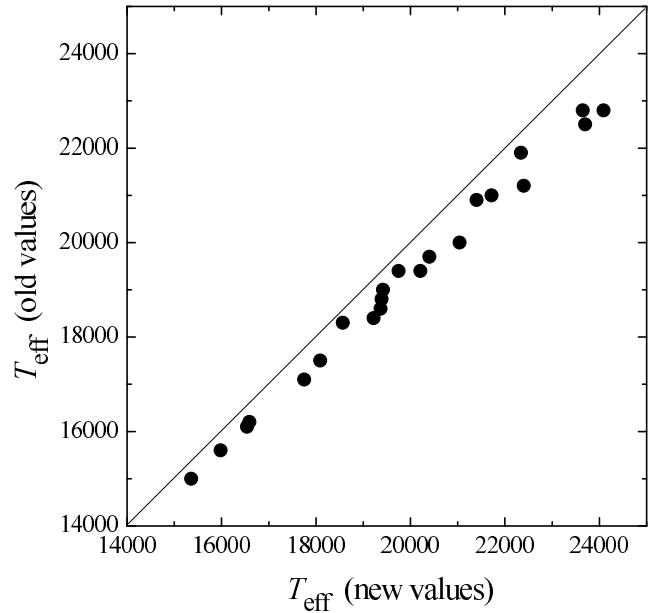


Figure 6. Comparison of the new T_{eff} and $\log g$ values with old parameters from Paper II.

from Table 1 with the old T_{eff} and $\log g$ values for the same 22 stars from Paper II. This comparison is shown in Fig. 6. One sees that new effective temperatures T_{eff} are slightly hotter than the old ones (upper panel). The mean difference is about 3 per cent, but for three hottest programme stars with T_{eff} close to 24000 K it reaches 4-5 per cent. This T_{eff} increment is mainly explained by the fact that now we added the second independent T_{eff} indicator, namely the index Q , which tends to increase T_{eff} in comparison with $[c_1]$.

Lower panel of Fig. 6 presents the comparison of new and old $\log g$ values. It is important to emphasize that our new surface gravities are found from stellar parallaxes and, therefore, are independent of model atmospheres of the stars. On the contrary, when the old $\log g$ values in Paper II were determined, the β -index and equivalent widths of the

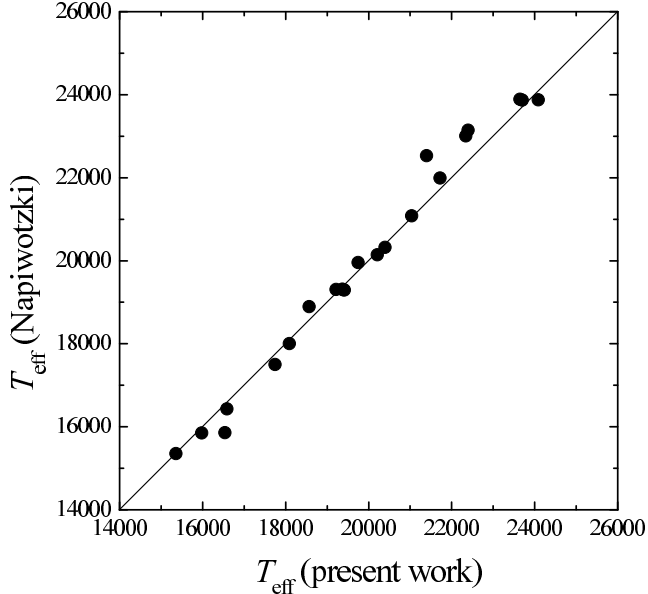


Figure 7. Comparison of our T_{eff} values with ones derived with Napiwotzki's (2004) code. The straight line corresponds to equal effective temperatures.

Balmer lines H_β and H_γ were used; their observed values were compared with results of model computations. In other words, the new and old $\log g$ values are derived by different methods. One may see that there is a marked difference between the new and old $\log g$ values for some stars. For instance, the stars HR 1640 and HR 8385 (marked in Fig. 6) show a difference of $+0.30$ and -0.26 dex, respectively. Errors in their new $\log g$ values are ± 0.15 and ± 0.10 dex, respectively (Table 1), so they can explain the discrepancy only partially. We believe that the new surface gravities $\log g$ derived from parallaxes are more reliable. It should be noted that the mean error of the $\log g$ values in Table 1 is ± 0.11 dex, whereas an accuracy of ± 0.2 or ± 0.3 dex was considered typical for B stars a few years ago. Thus, our surface gravities $\log g$ derived from stellar parallaxes are rather accurate.

What may we say about the accuracy of the derived effective temperatures T_{eff} ? To answer this question, we compare our T_{eff} values with evaluations based on two other accurate T_{eff} scales. Napiwotzki et al. (1993) provided the T_{eff} calibration for $[u - b]$, $(b - y)_0$ and $(B - V)_0$ using a sample of stars with well known temperatures. Later Napiwotzki (2004) presented a new calibration, which is based on colors derived from Kurucz's (1993) model atmospheres. A scale provided by Fitzpatrick & Massa (2005), which gives T_{eff} values in very good agreement with those derived with Napiwotzki's (2004) code, is based on a new calibration of synthetic photometry in various photometric systems for 45 normal nearby B and early A stars on the basis of Kurucz's (1993) model atmospheres. Fitzpatrick & Massa emphasize that their and Napiwotzki's calibrations 'have no input data in common'. In fact, these calibrations use different observables: Napiwotzki (2004) applies $uvby\beta$ photometry, whereas Fitzpatrick & Massa (2005) employ IUE spectrophotometry, V-band fluxes and *Hipparcos* parallaxes (old catalog, ESA 1997).

Table 3. Comparison of our parameters with those of Nieva & Simón-Díaz (2011) = NS'11 for two common stars, namely HR 1781 and HR 1820 (the NS'11 $\log \epsilon(\text{O})$ values are taken from Simón-Díaz, 2010)

Parameter	HR 1781 = HD 35299		HR 1820 = HD 35912	
	Present work	NS'11	Present work	NS'11
T_{eff} , K	23700 ± 410	24000 ± 200	19370 ± 380	19000 ± 300
$\log g$	4.27 ± 0.07	4.20 ± 0.08	4.05 ± 0.19	4.00 ± 0.10
V_t , km s^{-1}	1.2 ± 1.0	0 ± 1	0.8 ± 1.0	2 ± 1
$\log \epsilon(\text{C})$	8.25 ± 0.10	8.37 ± 0.07	8.28 ± 0.10	8.33 ± 0.09
$\log \epsilon(\text{N})$	7.76 ± 0.08	7.81 ± 0.07	7.76 ± 0.09	7.76 ± 0.07
$\log \epsilon(\text{O})$	8.68 ± 0.07	8.71 ± 0.08	8.71 ± 0.08	8.77 ± 0.12

Table 4. Comparison of our parameters and the C, N and O abundances with those of Nieva & Przybilla (2012) = NP'12 for four common stars

Parameter	HR 1781 = HD 35299		HR 1810 = HD 35708	
	Present work	NP'12	Present work	NP'12
T_{eff} , K	23700 ± 410	23500 ± 300	21040 ± 520	20700 ± 200
$\log g$	4.27 ± 0.07	4.20 ± 0.05	4.11 ± 0.07	4.15 ± 0.07
V_t , km s^{-1}	1.2 ± 1.0	0 ± 1	0.0 ± 1.0	2 ± 1
$\log \epsilon(\text{C})$	8.25 ± 0.10	8.35 ± 0.09	8.25 ± 0.12	8.30 ± 0.09
$\log \epsilon(\text{N})$	7.76 ± 0.08	7.82 ± 0.08	8.16 ± 0.07	8.22 ± 0.07
$\log \epsilon(\text{O})$	8.68 ± 0.07	8.84 ± 0.09	8.65 ± 0.06	8.82 ± 0.11
Parameter	HR 2928 = HD 61068		HR 8385 = HD 209008	
	Present work	NP'12	Present work	NP'12
T_{eff} , K	23650 ± 850	26300 ± 300	15360 ± 240	15800 ± 200
$\log g$	3.83 ± 0.11	4.15 ± 0.05	3.76 ± 0.10	3.75 ± 0.05
V_t , km s^{-1}	3.7 ± 1.0	3 ± 1	1.2 ± 1.0	4 ± 1
$\log \epsilon(\text{C})$	8.01 ± 0.10	8.27 ± 0.07	8.57 ± 0.19	8.33 ± 0.09
$\log \epsilon(\text{N})$	7.91 ± 0.10	8.00 ± 0.12	7.97 ± 0.12	7.80 ± 0.11
$\log \epsilon(\text{O})$	8.69 ± 0.11	8.76 ± 0.09	8.92 ± 0.12	8.80 ± 0.11

We show in Fig. 7 a comparison of our T_{eff} values from Table 1 with ones derived by us from $uvby\beta$ -photometry (Hauck & Mermilliod 1998) with Napiwotzki's (2004) code. One may see that there is very good agreement with Napiwotzki's T_{eff} scale and, therefore, with Fitzpatrick & Massa's scale. Note especially that no systematic discrepancy is seen. This agreement with these two independent accurate T_{eff} scales confirms the reliability of our new T_{eff} values.

Additional checks on the parameters are possible through comparisons for stars common to recent studies. For example, Nieva & Simón-Díaz (2011) studied 13 early B-type stars in the Ori OB1 association including derivations of the C, N and O abundances. Their sample includes two stars from Table 1, namely HR 1781 and HR 1820. We compare in Table 3 the parameters T_{eff} and $\log g$ of these stars from their and our work. One may see that there is very good agreement with the T_{eff} and $\log g$ values; the differences are within errors of the T_{eff} and $\log g$ determinations. It is important to note that Nieva & Simón-Díaz used quite different methods to us for their T_{eff} and $\log g$ determinations, i.e., their methods are based on the non-LTE analysis of lines of C, O, Si and Fe in two stages of ionization. So, the comparison with their data confirms the reliability of our new T_{eff} and $\log g$ values. Nieva & Simón-Díaz adopt as we do the Kurucz ATLAS model atmospheres.

Nieva & Przybilla's (2012) study of 29 early B stars contains four objects in common with our list. (Note that this 2012 paper determines T_{eff} and $\log g$ by the methods very similar to those used by Nieva & Simón-Díaz, 2011).

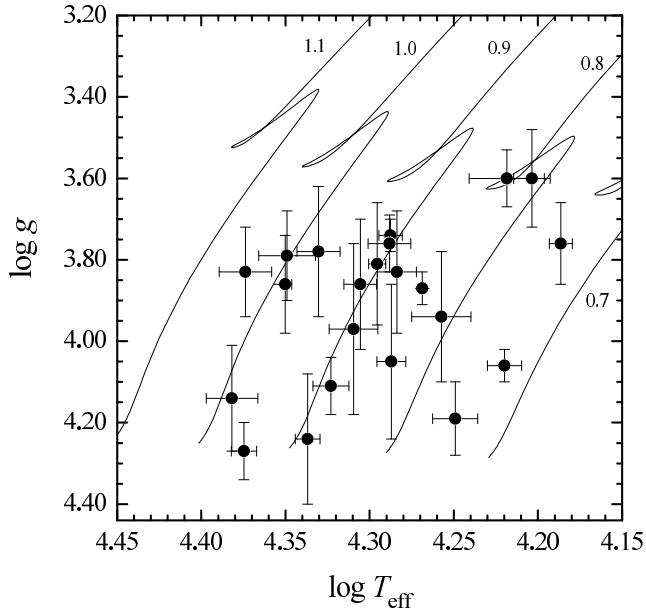


Figure 8. Claret’s (2004) evolutionary tracks and positions of programme stars on the $\log T_{\text{eff}} - \log g$ plane. Error bars in $\log T_{\text{eff}}$ and $\log g$ are shown for each star.

According to Table 4, there is good agreement between the parameters T_{eff} and $\log g$ of these stars and our values, except for HR 2928; for this star Nieva & Przybilla (2012) obtained a markedly hotter effective temperature T_{eff} and, as a result, the greater $\log g$ value. It should be noted that Napiwotzki’s (2004) method gives for HR 2928 the parameters $T_{\text{eff}} = 23980$ K and $\log g = 3.83$ that are very close to ours.

When basic parameters T_{eff} and $\log g$ are known, one may determine the mass M of a star from evolutionary tracks. The derived masses M of the programme stars (in the solar masses M_{\odot}) are presented in Table 1; they are found from Claret’s (2004) evolutionary tracks. One sees that the masses range from 5.4 to 11.2 M_{\odot} . The typical error in the M determination due to uncertainties in T_{eff} and $\log g$ is ± 8 per cent.

A question may arise about the reliability of stellar masses M_{ev} derived from evolutionary tracks. It is known that the most reliable masses M_{orb} are obtained for components of binaries from an analysis of their orbital elements. Lyubimkov (1996) compared the M_{ev} and M_{orb} values for a wide mass range; one may see from this comparison that there is very good agreement between M_{ev} and M_{orb} for masses between 5 and 15 M_{\odot} (see Fig. 9 there). So, we believe that our M values in the 5–11 M_{\odot} range inferred from Claret’s (2004) evolutionary tracks are rather accurate.

In Fig. 8 we show Claret’s (2004) tracks in the $T_{\text{eff}} - \log g$ plane, as well as locations of all 22 stars with corresponding error bars for T_{eff} and $\log g$; note that the labels for the tracks are $\log M/M_{\odot}$. One sees that all the stars are inside the MS band. Two stars, namely HR 7426 and HR 7996 with the lowest surface gravity $\log g = 3.60$, are close to the MS phase termination. Nonetheless, as mentioned in Section 2, the observed C, N and O abundances for such stars (they have $M \sim 6\text{--}7 M_{\odot}$ and $v \sin i \sim 30 \text{ km s}^{-1}$) are expected

Table 5. Carbon, nitrogen and oxygen abundances in atmospheres of 22 B-type MS stars. The number of lines used is shown in brackets.

HR	V_t km s $^{-1}$	$\log \epsilon(\text{C})$	$\log \epsilon(\text{N})$	$\log \epsilon(\text{O})$
38	2.7	8.29 ± 0.09 (9)	7.70 ± 0.06 (11)	8.56 ± 0.12 (8)
1617	0.5*	8.16 ± 0.06 (6)	7.63 ± 0.11 (11)	8.63 ± 0.15 (11)
1640	0.0	8.36 ± 0.13 (4)	7.78 ± 0.13 (11)	8.83 ± 0.11 (9)
1781	1.2	8.25 ± 0.10 (11)	7.76 ± 0.08 (23)	8.68 ± 0.07 (16)
1810	0.0	8.25 ± 0.12 (9)	8.16 ± 0.07 (13)	8.65 ± 0.06 (8)
1820	0.8	8.28 ± 0.10 (6)	7.76 ± 0.09 (19)	8.71 ± 0.08 (12)
1923	1.1	8.25 ± 0.06 (9)	7.74 ± 0.08 (20)	8.62 ± 0.06 (12)
1933	1.8	8.34 ± 0.14 (4)	7.81 ± 0.12 (12)	8.58 ± 0.10 (6)
2058	0.8	8.25 ± 0.09 (9)	7.72 ± 0.10 (22)	8.68 ± 0.09 (16)
2205	1.9	8.33 ± 0.09 (8)	7.76 ± 0.07 (20)	8.66 ± 0.07 (17)
2344	0.0*	8.21 ± 0.02 (3)	7.88 ± 0.20 (5)	8.73 ± 0.08 (5)
2756	0.0*	8.46 ± 0.19 (5)	7.82 ± 0.03 (4)	8.91 ± 0.07 (4)
2824	1.0	8.23 ± 0.10 (8)	7.66 ± 0.09 (22)	8.63 ± 0.12 (20)
2928	3.7	8.01 ± 0.10 (7)	7.91 ± 0.10 (19)	8.69 ± 0.11 (16)
3023	1.2	8.30 ± 0.12 (9)	7.79 ± 0.13 (16)	8.68 ± 0.11 (12)
7426	0.0*	8.30 ± 0.16 (9)	7.65 ± 0.13 (13)	8.59 ± 0.14 (9)
7862	2.0*	8.48 ± 0.12 (3)	7.86 ± 0.08 (6)	8.95 ± 0.10 (2)
7996	0.1*	8.53 ± 0.14 (3)	7.87 ± 0.09 (7)	8.84 ± 0.09 (4)
8385	1.2*	8.57 ± 0.19 (9)	7.97 ± 0.12 (11)	8.92 ± 0.12 (8)
8549	1.6	8.26 ± 0.07 (8)	7.74 ± 0.07 (20)	8.70 ± 0.07 (23)
8768	1.4	8.42 ± 0.10 (12)	7.86 ± 0.07 (20)	8.88 ± 0.16 (18)
9005	2.1	8.29 ± 0.09 (10)	7.84 ± 0.08 (22)	8.59 ± 0.07 (21)

*) These V_t values are determined in Paper III from He I lines

to be close to the initial ones; rotationally-induced mixing is not predicted to affect surface abundances unless a slow rotator is a rapid rotator seen at a high angle of inclination.

6 CARBON, NITROGEN AND OXYGEN ABUNDANCES

As mentioned above, model atmospheres for the stars were computed using Kurucz’s (1993) code ATLAS 9 for the derived parameters T_{eff} and $\log g$. When determining element abundances, apart from the star’s model atmosphere the microturbulent parameter V_t should be determined. We inferred the V_t values from N II and O II lines. A standard procedure was used, namely: we searched for the V_t that yields a zero slope for the abundance vs. W relation; in other words, no trend of the N and O abundances with equivalent widths W must exist. The derived parameters V_t (N II) and V_t (O II) were applied to the N and O abundance analyses, respectively. Since the few available C II lines are weak, the C abundance is only very slightly dependent on V_t ; we adopted the mean of the V_t (N II) and V_t (O II) – see Table 5. For the coolest programme stars, a reliable derivation of V_t from N II and O II lines is impossible, because the few available lines are weak. Therefore, for these stars (seven in all) we have taken V_t from He I lines (see Paper III); these V_t values are marked in Table 5 by asterisks. Table 5 shows that the V_t values for the programme stars are rather small: they vary from 0.0 to 3.7 km s $^{-1}$ with the average of 1.1 km s $^{-1}$. Of course, when all lines are weak, the derived abundance is independent of the adopted value of V_t .

The derived C, N and O abundances with the standard deviations from the line-to-line scatter for 22 programme stars are presented in Table 5. The number of C II, N II and O II lines used for each star is given there (in brackets). This

number depends on the effective temperature T_{eff} , and rotational velocity $v \sin i$, as well as the quality of the observed spectrum of a star. The C, N and O abundances are given in Table 5 as the mean values $\log \epsilon$ with the standard derivation σ . On average $\sigma = \pm 0.11$ dex for C and ± 0.10 dex for N and O. Averaging data from Table 5, we obtain the following mean C, N and O abundances: $\log \epsilon(\text{C}) = 8.31 \pm 0.13$, $\log \epsilon(\text{N}) = 7.80 \pm 0.12$ and $\log \epsilon(\text{O}) = 8.73 \pm 0.13$.

As mentioned above, the accuracy of the C, N and O abundances depends on the reliability of the basic parameters T_{eff} and $\log g$. In order to estimate the accuracy, one may compare the derived mean $\log \epsilon(\text{C})$, $\log \epsilon(\text{N})$ and $\log \epsilon(\text{O})$ values with results obtained only for the stars with the most reliable parameters T_{eff} and $\log g$. First, there are 11 stars in Table 1 with the relatively small temperature errors $\Delta T_{\text{eff}} < 500$ K; we found for them on average $\log \epsilon(\text{C}) = 8.34 \pm 0.13$, $\log \epsilon(\text{N}) = 7.78 \pm 0.09$ and $\log \epsilon(\text{O}) = 8.74 \pm 0.11$. Second, the most accurate $\log g$ values are obtained for the stars with small errors in the parallaxes π . There are 7 programme stars with the minimum errors in π , i.e., errors of ≤ 10 per cent. The mean abundances for these 7 stars are $\log \epsilon(\text{C}) = 8.28 \pm 0.10$, $\log \epsilon(\text{N}) = 7.81 \pm 0.18$ and $\log \epsilon(\text{O}) = 8.69 \pm 0.10$. Third, there are 4 common stars from both previous groups, which have simultaneously the most accurate T_{eff} and $\log g$ values; we found for them $\log \epsilon(\text{C}) = 8.30 \pm 0.13$, $\log \epsilon(\text{N}) = 7.74 \pm 0.08$ and $\log \epsilon(\text{O}) = 8.72 \pm 0.13$. One sees that in all three cases the mean C, N and O abundances virtually coincide with the above-mentioned averages for a total sample of 22 stars. It should be noted that van Leeuwen (2007) did not recommend use of parallaxes π with errors > 10 per cent. However, we found no marked difference in the mean C, N and O abundances between objects with errors in $\pi > 10$ per cent (15 stars) and ≤ 10 per cent (7 stars): the difference is 0.04, 0.00 and 0.05 dex for C, N and O respectively, and these values are less than uncertainties in the mean abundances.

We estimated typical errors in the derived C, N and O abundances, which originate from four contributors, namely uncertainties in the parameters T_{eff} , $\log g$ and V_t and the scatter in the $\log \epsilon$ estimates from various lines. Since equivalent widths of C II, N II and O II lines depend nonlinearly on T_{eff} (see, e.g., Figs 2 and 3), the contribution of the uncertainty in T_{eff} to a total error can be dependent on T_{eff} . We selected a number of the stars from Table 1, which represent the whole T_{eff} range, and estimated for them the total errors in $\log \epsilon(\text{C})$, $\log \epsilon(\text{N})$ and $\log \epsilon(\text{O})$ adopting the following mean uncertainties: $\Delta T_{\text{eff}} = \pm 500$ K, $\Delta \log g = \pm 0.11$ and $\Delta V_t = \pm 1.0$ km s $^{-1}$; the scatter in $\log \epsilon$ between lines is characterized by the mean dispersion $\sigma = \pm 0.10$ dex (see above). We found that the total error in $\log \epsilon(\text{C})$ varies from 0.17 to 0.11 dex when T_{eff} varies from 15000 to 24000 K; the total error in $\log \epsilon(\text{N})$ and $\log \epsilon(\text{O})$ varies from 0.18 to 0.11 dex and from 0.21 to 0.13 dex, respectively. The contribution of the uncertainty $\Delta V_t = \pm 1.0$ km s $^{-1}$ seems to be imperceptible for all temperatures T_{eff} as the lines used are rather weak. The contribution of the T_{eff} uncertainty increases with decreasing T_{eff} . For the hottest stars of our sample ($T_{\text{eff}} \sim 22000$ -24000 K) the errors in $\log \epsilon$ originate mostly from the scatter in $\log \epsilon$ between lines, whereas for the cooler stars ($T_{\text{eff}} \sim 15000$ -19000 K) the contribution of the T_{eff} uncertainty is significant.

Independent but limited confirmation of the accuracy

Table 6. Comparison of our mean C, N and O abundances with other recent results

Source	Number of stars	$\log \epsilon(\text{C})$	$\log \epsilon(\text{N})$	$\log \epsilon(\text{O})$
Present work	22	8.31 ± 0.13	7.80 ± 0.12	8.73 ± 0.13
Takeda et al. (2010)	64	-	-	8.71 ± 0.06
Nieva & Simón-Díaz (2011)	13 ^{a)}	8.35 ± 0.03	7.82 ± 0.07	8.77 ± 0.03
Cunha, Hubeny & Lanz (2012)	10 ^{a)}	-	-	8.78 ± 0.05
Nieva & Przybilla (2012)	29	8.33 ± 0.04	7.79 ± 0.04	8.76 ± 0.05

^{a)} stars in the Ori OB1 association

of our C, N and O abundances is presented in Table 3, where our and Nieva & Simón-Díaz's (2011, hereinafter NS'11) data for two common stars from the Ori OB1 association are compared. The derived C, N and O abundances show very good agreement: differences in the $\log \epsilon(\text{C})$, $\log \epsilon(\text{N})$ and $\log \epsilon(\text{O})$ values vary from 0.00 to 0.06 dex, i.e. they are markedly less than errors of the $\log \epsilon(\text{C})$, $\log \epsilon(\text{N})$ and $\log \epsilon(\text{O})$ determination with only the C abundance for HR 1781 showing a greater difference, namely 0.12 dex.

In the same vein, we compare in Table 4 our C, N and O abundances with data of Nieva & Przybilla (2012, hereinafter NP'12) for four common stars. In particular, one sees from Table 4 that the above-mentioned enhanced N abundance for HR 1810 is confirmed by NP'12. In general, an agreement between our and NP'12 results is worse than for two stars from NS'11 (Table 3). Especially large discrepancies with NP'12 are found for the C abundances in HR 2928 and HR 8385 (+0.26 and -0.24 dex, respectively). Note that in the case of HR 2928 the discrepancy is partially explained by the substantial difference between the adopted T_{eff} values.

It should be noted that the C, N and O abundances derived in NS'11 and NP'12 show no correlation with the effective temperature T_{eff} (see Fig.7 in NP'12). Our N and O abundances show no dependence on T_{eff} , too. However, unlike N and O, the C abundances for cooler stars of our sample with $T_{\text{eff}} \leq 18000$ K seem to be somewhat higher than for hotter stars. In fact, the mean value is $\log \epsilon(\text{C}) = 8.46 \pm 0.09$ for the stars with $T_{\text{eff}} < 18100$ K (6 objects) and $\log \epsilon(\text{C}) = 8.25 \pm 0.08$ for the stars with $T_{\text{eff}} > 18500$ K (16 objects). Note that there are only two relatively cool B stars in NS'11 and NP'12 with $T_{\text{eff}} < 18000$ K; their C abundances derived from C II lines are in good agreement with the $\log \epsilon(\text{C})$ values for other stars. On the one hand, marked difference in the C abundances between the stars of our sample with $T_{\text{eff}} < 18100$ K and $T_{\text{eff}} > 18500$ K can result from some incompleteness of the used C model atom (in NS'11 and NP'12 the updated model is applied). On the other hand, it is interesting that the mean value $\log \epsilon(\text{C}) = 8.46$ for the cooler stars agrees very well with the solar C abundance, whereas the mean value $\log \epsilon(\text{C}) = 8.25$ for the hotter stars (as well as the mean C abundances in NS'11 and NP'12) show a marked underabundance.

7 DISCUSSION

When our work was in progress, a several interesting publications appeared with C, N and O abundances in B stars. In

Table 7. The mean C, N and O abundances for the B-type MS stars in comparison with the solar abundances

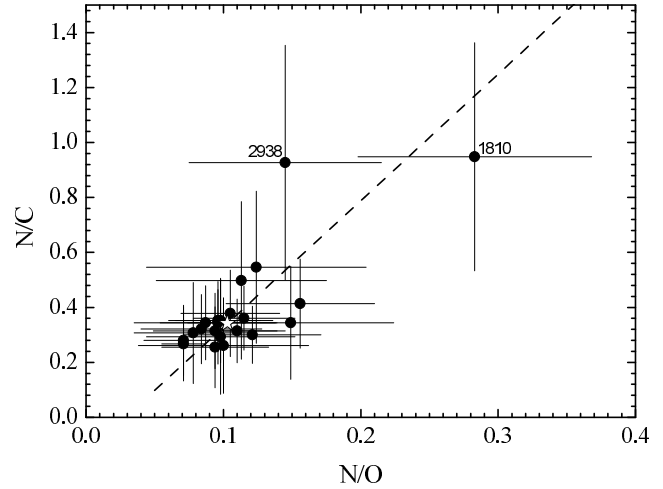
Object	$\log \epsilon(\text{C})$	$\log \epsilon(\text{N})$	$\log \epsilon(\text{O})$	Source
B-type stars	8.31 ± 0.13	7.80 ± 0.12	8.73 ± 0.13	Present work
Solar	8.50 ± 0.06	7.86 ± 0.12	8.76 ± 0.07	Caffau et al.
photosphere				(2008, 2009, 2010)
Solar	8.43 ± 0.05	7.83 ± 0.05	8.69 ± 0.05	Asplund et al.
photosphere				(2009)
Protosolar	8.47 ± 0.05	7.87 ± 0.05	8.73 ± 0.05	Asplund et al.
abundances				(2009)

Table 6, we compare our mean C, N and O abundances with these recent results. Some of the 64 B stars from Takeda et al.'s (2010) sample are close to or beyond the termination of the MS (see their Fig.1). However, due to the relatively low masses ($M = 3\text{--}9 M_{\odot}$) and slow rotational velocities ($v \sin i \leq 30 \text{ km s}^{-1}$), these stars are expected to have retained their initial surface C, N and O abundances. Takeda et al. determined the O abundance from the O I 6156 Å multiplet, and the Ne abundance from Ne I lines but did not provide either C or N abundances. Of the 29 early B stars analysed by NP'12, most are caught well before the end of the MS (see Fig. 5 there). An obvious exception is the star α Pyx (HR 3468, HD 74575) with the lowest surface gravity $\log g = 3.60$, which is close to the MS's termination. Its mass is $M \approx 12 M_{\odot}$ and the projected rotational velocity is $v \sin i = 11 \text{ km s}^{-1}$; according to (Frischnecht et al. 2010) and assuming the star is not a rapid rotator observed at a high angle of inclination, such a star cannot change markedly its surface C, N and O abundances during the MS phase. On the whole, one may suppose that the vast majority of the C, N and O abundances presented in Table 6 correspond to the initial abundances in these young stars.

Table 6 shows that our mean C, N and O abundances are in very good agreement with data from recent papers. In particular, there is excellent agreement with the mean C, N and O abundances found in NS'11 and NP'12. This is very important because both in the T_{eff} and $\log g$ determination and in the CNO abundance analysis quite different techniques were used by NS'11 (and NP'12) and us.

It should be noted that NS'11, as well as Cunha, Hubeny & Lanz (2012), studied the unevolved early B stars in the Ori OB1 association. In both studies, the T_{eff} range of the stars is displaced to hotter temperatures relative to our sample: 19000–33400 K for NS'11 against 15360–24090 K for our sample. The agreement over abundances extends to Mg: 7.57 ± 0.06 from NS'11 and 7.59 ± 0.15 from Paper IV.

Since the Ori OB 1 stars have been formed from interstellar material of the (presumed) same metallicity, it is quite natural that they show very homogeneous initial C, N and O abundances. In contrast, the scatter in the individual $\log \epsilon(\text{C})$, $\log \epsilon(\text{N})$ and $\log \epsilon(\text{O})$ values for the stars of our sample is greater than for the above samples from Ori OB 1. However, the stars of our sample do not belong to a single cluster or association; on the contrary, they are distributed around the solar neighbourhood up to $d = 600 \text{ pc}$. Therefore, we speculate that the spread among the individual $\log \epsilon(\text{C})$, $\log \epsilon(\text{N})$ and $\log \epsilon(\text{O})$ values for our stars may be augmented by real star-to-star variation in the initial C, N and O abundances; the Galactic abundance gradient may be one source of the variation.

**Figure 9.** Relation between the mass ratios N/C and N/O for 22 programme stars. Two stars with the high N/C values, namely HR 1810 and HR 2938, are marked. Theoretical path of the N/C vs. N/O relation is shown by the dashed line drawn through the initial values $N/O = 0.103$ and $N/C = 0.342$ (open star in the figure) with a slope $d(N/O)/d(N/C) = 4.6$ from NP'12.

In Table 7 our mean $\log \epsilon(\text{C})$, $\log \epsilon(\text{N})$ and $\log \epsilon(\text{O})$ values for 22 B stars are compared with the recent solar values (Caffau et al. 2008, 2009, 2010; Asplund et al. 2009). Protosolar abundances are 0.04 dex larger (Asplund et al. 2009). When comparing the results in Table 7, we conclude that our mean $\log \epsilon(\text{N})$ and $\log \epsilon(\text{O})$ values for the B stars coincide within errors of their determination with the photospheric and protosolar abundances. However, our mean $\log \epsilon(\text{C})$ value, also those in NS'11 and NP'12 (Table 6), shows a marked underabundance in comparison with the Sun (the deficiency is especially noticeable when compared with small errors in the mean C abundances in NS'11 and NP'12).

We also determined the ratios N/O and N/C for 22 programme stars; we found the mean values $\log (N/O) = -0.91 \pm 0.13$ and $\log (N/C) = -0.50 \pm 0.15$. The first value is very close to the solar ratio $\log (N/O) = -0.90 \pm 0.14$ (Caffau et al.) or -0.86 ± 0.07 (Asplund et al.). The second one is somewhat greater than the solar ratio $\log (N/C) = -0.64 \pm 0.13$ (Caffau et al.) or -0.60 ± 0.07 (Asplund et al.); a main cause of this difference is a slight C deficiency in B stars.

Following to NP'12 (see their Fig.14), we show in Fig.9 the N/C vs. N/O diagram, where the derived CNO abundances, like NP'12, have been converted into the mass fraction scale. One may see that there is no correlation between N/O and N/C for the most of the stars; this is explainable because their observed CNO abundances are expected to correspond to the unchanged initial values. However, two of the stars, namely HR 1810 and HR 2938, show the relatively high N/C values. One may suppose that these two stars could change their atmospheric abundances of light elements during the MS phase evolution due to the rotationally induced mixing. However, their positions in the $T_{\text{eff}} - \log g$ diagram (Fig.8) are not exclusive. Moreover, the presented errors in the N/O and N/C values for these stars are large (note that the errors in Fig.9 are proportional to N/O and

Table 8. Comparison of our mean C, N and O abundances for 20 B stars (the ‘mixed’ stars HR 1810 and HR 2928 are omitted) with a present-day Cosmic Abundance Standard (CAS) from NP’12

Element	Our abundances	CAS (NP’12)
C	8.33±0.11	8.33±0.04
N	7.78±0.09	7.79±0.04
O	8.72±0.12	8.76±0.05

N/C themselves), so their difference from other stars cannot recognize as a reliable one. Nevertheless, it should be noted that the relatively high N/C ratios for HR 1810 and HR 2938 were confirmed by NP’12.

We also display in Fig.9 a possible theoretical trend (dashed line) which corresponds to the NP’12 slope $d(N/O)/d(N/C) = 4.6$ and our initial values $N/O = 0.103$ and $N/C = 0.342$ found for 20 stars without HR 1810 and HR 2938 (open star in Fig.9); note that these initial values are very close to the NP’12 ones. When excluding for the assumptive mixed stars HR 1810 and HR 2938, we obtain the following mean abundances for the remaining 20 stars: $\log \epsilon(C) = 8.33 \pm 0.11$, $\log \epsilon(N) = 7.78 \pm 0.09$ and $\log \epsilon(O) = 8.72 \pm 0.12$. We compare in Table 8 these values with a present-day Cosmic Abundance Standard (CAS) of NP’12; one sees that there is an excellent agreement.

Thus, our findings, as well as up-to-date data of other authors show that the observed (unevolved) N and O abundances in B stars are very close to the solar ones. On the other hand, carbon shows a small stable deficiency. In fact, using the old carbon model atom of Sigut (1996), we found the mean abundance $\log \epsilon(C) = 8.31 \pm 0.13$. Basing on the updated carbon model atom, NS’11 and NP’12 obtained the very close values 8.35 ± 0.03 and 8.33 ± 0.04 , respectively (note that errors are very small there). All these values are markedly lower than the current $\log \epsilon(C)$ evaluations for the Sun (Table 7). It is important to note that many other chemical elements show abundances that are in an excellent agreement with the solar ones (see Introduction). Why does only carbon show such a unique difference from the Sun’s abundance?

It is possible that there are some specific details in non-LTE computations of C II lines that were ignored up to now. In particular, the C II ionization energy is $E_{\text{ion}} = 24.383$ eV that corresponds to the wavelength $\lambda = 508.5$ Å; therefore, the C II photoionization is controlled by the EUV radiation. For example, such a radiation was observed for the star ϵ CMa (B2 II); it was found that the observed EUV flux at $\lambda < 504$ Å (He I continuum) is significantly greater than the computed one (Cassinelli et al. 1995). Later Gregorio et al. (2002), using both the ATLAS9 model atmospheres of Kurucz (1993) and the spherical model atmospheres of Aufdenberg et al. (1999), showed that a more satisfactory agreement with the observed EUV flux for the star ϵ CMa can be achieved; however, the observed flux has a different shape than the predicted one. Moreover, the observed line intensities in this region seem to be much stronger than predicted ones. Thus, the theory cannot describe adequately the EUV flux which is important for computations of the C II photoionization (as well as the N II and O II photoionization, too). Moreover, we cannot exclude that some

further update of the carbon model atom is needed to solve the problem.

Another alternative was proposed recently; it was supposed that the Sun can migrate during its life (i.e., for the past $4.5 \cdot 10^9$ yr) from inner parts of the Galactic disk where it has born, so its observed chemical composition may differ from the composition of young stars in its present neighbourhood (typical ages of the B stars in question are $t \sim (10 - 100) \cdot 10^6$ yr). This hypothesis is discussed, e.g., in NP’12 (see also references there). Detailed analysis of the radial migration of stars (including the Sun) within the Galaxy is very hard; nevertheless, the question remains: why is it that only the carbon abundance shows a marked difference from the Sun’s abundances? In our opinion, the slight carbon deficiency in the unevolved B stars is a subject for further discussion.

8 CONCLUDING REMARKS

We selected from our original list of early and medium B-type stars (Paper III) the relatively cool stars with low rotational velocities ($v \sin i < 70$ km s⁻¹). Their two basic parameters, namely the effective temperature T_{eff} and the surface gravity $\log g$ were redetermined; application of new stellar parallaxes allowed increasing markedly the accuracy of the derived $\log g$ values. Our final list contains 22 stars with the following parameters: (i) effective temperatures T_{eff} are less than 24100 K; (ii) surface gravities $\log g$ are mostly greater than 3.75; (iii) the projected rotational velocities are $v \sin i \leq 66$ km s⁻¹. These stars with moderate masses $M = 5-11 M_{\odot}$ and slow rotation should keep their initial surface C, N and O abundances according to the theory of rotationally-induced mixing.

We found for these stars the mean abundances $\log \epsilon(C) = 8.31 \pm 0.13$, $\log \epsilon(N) = 7.80 \pm 0.12$ and $\log \epsilon(O) = 8.73 \pm 0.13$; we suppose that these values are the initial CNO abundances in B-type MS stars. The derived N and O abundances coincide with the solar values, whereas the C abundance is somewhat lower than the solar one. We showed that these C, N and O abundances are in good agreement with the recent values for B-type MS stars by other authors. In particular, the small C deficiency is confirmed by the recent studies by NS’11 and NP’12.

Two programme stars, namely HR 1810 and HR 2938, can be mixed during the MS phase. If these stars are omitted, we obtain the following mean abundances for the remaining 20 stars: $\log \epsilon(C) = 8.33 \pm 0.11$, $\log \epsilon(N) = 7.78 \pm 0.09$ and $\log \epsilon(O) = 8.72 \pm 0.12$; these values are in excellent agreement with a present-day Cosmic Abundance Standard (CAS) of Nieva & Przybilla (2012).

Thus, on the one hand, the initial N and O abundances in nearby B-type stars, as well as the abundances of some other metals, confirm that young stars in the solar neighbourhood and the Sun have the same metallicity. In the absence of a migration of the Sun from its birthplace, one may conclude that during the Sun’s life (i.e., for the past $4.5 \cdot 10^9$ yr) the metallicity of the solar neighbourhood has not markedly changed; so, an intensive enrichment of the solar neighbourhood by metals occurred before the Sun’s birth. On the other hand, carbon is an evident ‘outlier’ in this scenario, because the observed C abundance in B stars

shows a small deficiency in comparison with the Sun. This carbon deficiency demands an alternative hypothesis either the Sun has migrated from inner parts of the Galactic disk where it has born or present non-LTE computations overlook one or more physical effects in the carbon ions. The C underabundance in B stars needs further study.

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